Varying "constants" in cosmology and astrophysics and...

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Abstract. We review astrophysical, cosmological and terrestrial evidence for and against the constancy of fundamental parameters of particle physics, and discuss theoretical issues of unification and scalar-mediated forces, finding that the current rate of variation is bounded by limits on violations of the weak equivalence principle.

Introduction. The constancy of the parameters of particle physics [1], such as the fine structure expansion parameter α of electromagnetism, is an assumption that should be tested, since new physics has often arisen from the breakdown of assumptions.

At present not all tests are unambiguously consistent with constancy, and there is a theoretical framework, involving extending particle physics models with one or more cosmologically varying scalar fields [2], which can lead to interesting constraints and predictions. Experiments are continuously being improved and updated and we can expect many puzzles to be resolved within a few years.

This talk summarizes the techniques and results in cosmology, astrophysics, nuclear physics and atomic physics in investigating the alleged constancy of physical parameters, and outlines a current research project on primordial nucleosynthesis (BBN). We also focus on two theoretical questions: first, whether we can relate independently measurable parameters such as α and the proton-electron mass ratio μ in unified theories; second, what long-range forces may result from the scalar fields which are posited to be the source of nonzero variation?

Relation to postulates of General Relativity. The variation of (locally) measurable physical parameters over spacetime violates Local Position Invariance which is part of the Einstein Equivalence Principle. Still, "varying constants" may be studied within a generally covariant theory where scalar degrees of freedom are excited. As we will see, the universality of free fall, another essential postulate in GR, may also be violated due to the scalar coupling to matter.

Atomic and molecular transitions. The most exact and direct measurements of fundamental parameters come from electromagnetic transitions in atoms and molecules, measured by various optical techniques. Since all such transitions are proportional to the Rydberg constant one must measure two or more to constrain the value of a dimensionless parameter. Different transitions have different functional dependence on α and $\mu \equiv m_p/m_e$ (and on magnetic moments [3]).

Atomic clocks. By measuring two or more different atomic transitions over several years (for example the SI frequency standard, a hyperfine transition of ^{133}Cs) one can limit the present rate of change of various fundamental parameters. Limits on $\dot{\alpha}/\alpha$ of 3×10^{-15} per year have been achieved [4] using atomic hydrogen, mercury and caesium, and $2\times10^{-15}\,\mathrm{y}^{-1}$ with transitions of a single Yb$^+$ ion [5].

Astrophysical spectra. Quasar absorption spectra offer a means to probe the values of fundamental parameters over cosmological time, though with much less absolute accuracy than atomic clocks. One looks for absorption lines which have a high sensitivity to α (or some other parameter) and are optically distinct and not saturated. Since the redshift of each system is a priori unknown, at least two transitions must be measured. Fitting to the velocity profiles of absorption systems introduces an uncertainty whose size is debatable in each individual system but should average to zero over many systems (as should differential velocities between different species). A nonzero fractional variation of α is claimed [6] at the level $(-0.57\pm0.11)\times10^{-5}$ (average over 143 systems with $0.2<z<4.2$); this is contradicted by null results with quoted accuracy down to 0.15×10^{-5} derived from a relatively small number of systems [7].

Recently the proton-electron mass ratio was measured to have varied significantly from the current value: the claimed fractional variation [8] is $(2.4\pm0.6)\times10^{-5}$, from two molecular hydrogen systems at redshift around 3. Other dimensionless physical parameters may also be probed, and null results have been obtained for the fractional variations of the products $\alpha^2 g_p$ and $\alpha^2 g_p/\mu$ at an accuracy of 10^{-5} [9].

Nuclear physics. Nuclear phenomena are more complicated than atomic or molecular transitions since they involve the strong nuclear force, which is now understood as the residual effects of QCD acting between particles with confined colour charges. The QCD confinement scale Λ_c can be taken as a fundamental energy scale or unit for hadronic and nuclear processes; then the relevant parameters are α and the Fermi constant G_F, plus the light quark masses which affect the masses and interactions of both hadrons and mesons. Most nuclear reactions involve more than one type of interaction, thus they depend nontrivially on more than one parameter leading to possible degeneracies.

Nuclear physics effects at distant epochs can only be probed indirectly, via astronomical measurements of relative isotopic abundances, or measurements of asteroids or rock samples on Earth.

Oklo. Isotopic ratios of many elements in the Oklo uranium mine in Gabon differ strikingly from values obtained elsewhere on Earth, indicating that extensive nuclear reactions occurred there at some past epoch. The higher fraction of ^{235}U in the past, combined with an unusual rock formation and water moderation of neutrons allowed a fission chain reaction to occur. By comparing isotopic ratios of different elements one can deduce whether their cross-sections for neutron capture σ_n (averaged over an estimated neutron energy distribution) had the same ratio at the time of the reactor operation (1.8 billion years ago, $z\simeq1.3$) as today. Then if the dependence of σ_n on (*e.g.*) α is known for different isotopes, a bound on α can be deduced up to possible degeneracies. The strongest bound arises from the ^{149}Sm$/^{147}$Sm ratio: ^{149}Sm has a sharp neutron capture resonance whose α dependence is enhanced by accidental cancellation of nuclear *vs.* electromagnetic energy; the fractional variation of α is thus limited below 10^{-7} [10].

Other bounds can be obtained from considering decays in meteorites believed to have formed around the same time as the Solar System [11], although these are also subject to degeneracy and can only test the averaged values of parameters over billions of years. Nuclear data can also be interpreted as bounding the variation of quark masses, but the dependence of nuclear forces on quark masses is still subject to much theoretical uncertainty, requiring further efforts in lattice and effective field theory.

Primordial nucleosynthesis (BBN). The isotopic composition of matter in the early Universe is a witness to nuclear reactions that proceeded in the hot plasma soon after the Big Bang. Starting with protons and neutrons in equilibrium, models based on laboratory measurements of cross-sections are used to track the progress of reactions and predict the resulting abundances of light elements. These can be compared with astronomical observations which attempt to measure nuclear abundances in stars or gas and extrapolate back to a point where the effects of astrophysical processing were negligible. The clearest test is deuterium which is only destroyed in astrophysical processes, hence any measurement of D/H is a lower bound on the primordial value. Other isotopes considered are ^{4}He, which accurately reflects the neutron-proton ratio at the time when free neutrons are bound into nuclei, ^{3}He and ^{7}Li. Other than ^{4}He, the light element abundances in standard BBN reflect mainly the baryon fraction since the progress of the relevant reactions depends mainly on the concentration of particles. However, if we consider possible variations in fundamental parameters, different reactions and abundances may be affected in various ways, and in principle many different parameters could be bounded simultaneously [14].

Disadvantages of nucleosynthesis as a probe of fundamental parameters are the large observational uncertainties; the complexity of the reaction network; and theoretical uncertainty in the dependence of nuclear reactions on QCD parameters. Advantages are the very large redshift (about 10^{10}) making it the earliest direct test; the independent WMAP estimate of the baryon fraction, which removes one unknown from the system; and the possibility of bounding many parameters at once, since nuclear reactions depend on the strong, electromagnetic and weak forces and freezeout is governed by the expansion of the Universe (*i.e.* gravity). Work is continuing with C. Wetterich and S. Stern to find a complete set of such bounds, incorporating recent advances in nuclear theory.

Theoretical issues. The only consistent way to introduce non-constant fundamental parameters in theory appears to be a cosmological scalar field, which reduces the variation to a property of the particular solution we inhabit, rather than the underlying theory. In order to have non-negligible variation over cosmological times or distances, the scalar should be extremely light, and either be "rolling" freely in a very shallow potential, or be driven by the local matter density which is itself varying. Additionally there must be a coupling that induces a variation in observable quantities. This leads to the possibility of long range forces due to the scalar couplings, thus objects in free fall may not accelerate equally: this violates the weak equivalence principle (WEP).

In the low energy limit the scalar couples in general to electromagnetic energy and to the nucleon and electron masses: variations in α and μ are then related to the size of couplings and the variation of the scalar. This variation is bounded above via the effect of its kinetic energy on the expansion of the Universe. Hence for a given variation in α or μ we expect the differential acceleration η of two test bodies to be bounded below.

We also require some relations between different scalar couplings to electromagnetism and matter: such relations arise from unified scenarios [12] where all observable variations arise from one underlying varying quantity such as a grand unified gauge coupling α_X. Such relations can also be tested by comparing the sizes of $\Delta\ln\alpha$ and $\Delta\ln\mu$, if nonzero. We find for example [13]

$$\eta \geq \frac{\Delta_{12} f_p}{2\overleftarrow{\phi}^2_{\max}} \frac{K}{c_2^2} \left(\frac{\dot{\mu}}{\mu}\right)^2 \simeq \frac{K}{c_2^2} \left(\frac{\dot{\mu}/\mu}{3.7\times 10^{-10} y^{-1}}\right)^2 \tag{1}$$

where $\Delta_{12} f_p$ is the difference in proton fraction between two test bodies, $\overleftarrow{\phi}_{\max} \simeq 5\times 10^{-11} y^{-1}$ is the maximum allowed time derivative of the (dimensionless) scalar, and K and c_2^2 are numbers of order 1 which depend on the details of the unified theory. If a nonzero variation does exist, the presence or absence of WEP violation could test unified scenarios; conversely, bounds on WEP violation imply limits on the present rate of change of fundamental parameters, comparable with those from atomic clocks.

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